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RESEARCH MEMORANDUM

INVESTIGATION OF IGNITION CHARACTERISTICS OF AN-F-32 AND TWO AN-F-58a FUELS IN SINGLE CAN-TYPE TURBOJET COMBUSTOR

By Warren D. Rayle and Howard W. Douglass

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

An investigation was conducted to determine the ignition characteristics of three typical turbojet-engine fuels (AN-F-32 and two blends of AN-F-58a) in a single can-type combustor. Data obtained over ranges of simulated engine speed and altitude at two flight speeds and over a range of ambient temperature at sea-level static conditions showed the fuel-flow rates required for ignition as functions of fuel characteristics and operating conditions.

The fuel flow required for ignition in the combustor was found to increase with increasing simulated engine speed, with increasing simulated altitude, and with decreasing sea-level ambient temperature. At high altitudes and low ambient temperatures, the fuel flow required for ignition was found to be much greater than the fuel flow required for engine operation. A direct relation was found between the required fuel flow and the A.S.T.M. 10-percent evaporated temperature of the fuel.

INTRODUCTION

The use of turbojet engines over wide ranges of operating conditions involves not only problems of combustor stability and efficiency (reference 1) but also problems of fuel ignition. Ignition may be required either at sea level over a wide range of climatic conditions or during flight over a wide range of altitude and flight-speed conditions.

Factors that appear to deserve consideration in an investigation of ignition in a given engine are:

1. Air-flow parameters, which include mass-flow rate, temperature, pressure, and humidity at the combustor inlet and are determined by the conditions of the ambient air, the engine speed, and the flight speed

2. Fuel, which includes chemical and physical characteristics of the fuel as well as flow rate, temperature, and injection method

3. Ignition source, which includes location, intensity, and type of ignition source 1396

A general program for the investigation of these factors has been undertaken at the NACA Lewis laboratory. Experimentation to date has dealt with the boundary region between ignition and nonignition zones.

The data presented herein were obtained from August 1949 to February 1950 with three typical turbojet-engine fuels in a single can-type combustor operating at inlet-air conditions corresponding to engine operation at speeds of 1600, 2500, and 4000 rpm, altitudes from sea level to 30,000 feet, and flight Mach numbers of 0 and 0.6. In addition, sea-level data were obtained simulating operation at ambient temperatures from 90° to -36° F. The fuel-flow rate was treated as the dependent variable, whereas the fuel-composition and the air-flow parameters were considered independent variables. The fuel temperature was controlled to approximate the ambient-air temperature for each simulated condition. The humidity of the air was considered of secondary importance and was not controlled. The standard injection and ignition systems were used for this combustor.

FUELS

Three jet-propulsion fuels were selected for the ignition studies. The first (NACA fuel 48-306) met AN-F-32 specifications and was chosen as a reference fuel. The second (NACA fuel 49-162), which had the maximum permissible aromatic content, was a blend of manufacturer's AN-F-58a base stock, redistilled hydroformate bottoms, and number 3 fuel oil. The third (NACA fuel 49-245) was a blend of AN-F-58a base stock and isopentane and had a Reid vapor pressure of 7 pounds per square inch, the maximum permitted by the AN-F-58a specifications.

Complete fuel analyses and specifications are given in table I. Distillation curves are presented in figure 1.

APPARATUS AND PROCEDURE

The single-combustor installation used in this investigation is substantially the same as that employed in previous work (reference 2). Additions to the instrumentation included a photoelectric recording potentiometer connected to a fine wire thermocouple in the fuel-nozzle tip and an oscilloscope used to study spark-plug behavior.

Some modifications were made, chiefly to the fuel system, to permit a constant and measured flow of fuel to be injected to the combustor at 1396 the temperature and pressure desired. A sketch of the modified fuel system is presented in figure 2. The flow rate was controlled by the valve located immediately downstream of the fuel heater. The desired temperature was established by proportioning the fuel flow through the cooler and its by-pass line. A three-way solenoid valve was used to direct the fuel either through the return line, where the pressure was regulated by a valve, or to the injection nozzle.

With this system, a critical fuel flow was determined for each fuel at each simulated condition as follows:

1. The air flow, the pressure, and the temperature at the combustor inlet were fixed according to control curves (fig. 3) obtained by extrapolation of the engine-manufacturer's performance data using NACA standard atmosphere tables (reference 3).

2. The fuel flow through the drum return line was adjusted to the desired value while the fuel temperature and pressure, as measured at the three-way solenoid valve, were set to the ambient temperature and the required nozzle pressure, respectively.

3. The solenoid valve was energized, sending the fuel through the nozzle. This process was repeated at varying fuel flows until the demarcation between ignition and nonignition was defined. The critical fuel flow for the given condition was taken as a midpoint between the highest flow that failed to ignite and the lowest flow that ignited.

During these runs, the fuel-injection nozzle and the spark plug used were standard engine parts.

Data for the sea-level conditions and a flight Mach number of 0.6 were incomplete because the spark plug, operated from a 5000-volt source, was inadequate to provide a spark at these conditions. This failure was confirmed by observing the oscilloscope traces.

The fuel temperature, as observed from the thermocouple inserted in the fuel-nozzle tip, remained essentially at inlet-air temperature during each run because of the residual fuel contained in the nozzle and its holder. Preinjection control of fuel temperatures to ambient conditions was therefore of little direct consequence.

Because very little fuel was actually burned, a single drum sufficed for a considerable time and a decrease in volatility due to normal evaporation losses was therefore expected. Samples of the fuel taken at the beginning and the end of the drum of fuel and tested for Reid vapor pressure, refractive index, and specific gravity showed no significant change in fuel properties. 1396

In order to determine the effects of fuel-flow rate and temperature on the spray characteristics, a photographic survey was made utilizing an electronic flash unit. In these studies, the spray was directed downward into quiescent air in a glass-walled chamber.

RESULTS AND DISCUSSION

Data obtained over the ranges investigated are listed in table II, which includes the following for each operating condition: the minimum rate of fuel flow at which ignition occurs W_{f+}; the maximum rate of fuel flow at which ignition fails to occur W_{f-}; and the midpoint $W_{f,c}$ between these two preceding values. These critical fuel flows $W_{f,c}$ are plotted in figure 4.

The variation of critical fuel flow with ambient temperature at sea level and a Mach number of 0 (fig. 4(a)) shows that at the lower ambient temperatures higher fuel-flow rates are required for ignition. (Regions of ignition and nonignition are indicated by the arrows above the curves.) Such a trend may be attributed primarily to a decrease in combustor inlet-air temperature and to an increase in the mass-flow rate, inasmuch as the change of inlet-air pressure with ambient temperature is relatively small (fig. 3(a)). Comparison of individual curves indicates that an increase in engine speed, with the attendant rise in inlet-air temperature, pressure, and mass flow, demands an increase in fuel flow for ignition. Similarly, these curves indicate an inverse relation between critical fuel flow and volatility. (Reid vapor pressure values are given in table I.) The appearance of the curves indicates the possible existence of a minimum ambient temperature for ignition for each fuel and engine speed; that is, for each curve the slope may become zero at some ambient temperature.

Curves in figures 4(b) and 4(c) show the effect of altitude conditions on critical fuel flows at flight Mach numbers of 0 and 0.6, respectively. The trend is toward higher flow rates with higher altitudes, even with the diminishing air-flow rate that is attendant to an increase in altitude. All three inlet-air parameters (temperature, pressure, and mass-flow rate) are affected by increase in altitude; hence, the basic factor or combination of factors causing this behavior may not be extracted from these data. The relations of critical fuel flow to engine speed and to fuel volatility at altitude conditions are, in general, the same as at various sea-level ambient temperature conditions, although some anomalies are apparent.

The critical fuel flows considered in this report might be more descriptively termed "lower critical fuel flows" below which ignition is improbable. At some 20,000- and 30,000-foot altitude conditions, however, observations indicated the existence of "upper critical fuel flows" above which ignition is improbable. This upper boundary region was not investigated because only a small portion thereof would lie within the safe and practical limits of the equipment. The narrowing range of fuel-flow rates for ignition at high altitudes is analogous to the narrowing inflammable range of fuel-air ratios at low pressures obtained in bench-scale determinations of the inflammability limits of fuel-air mixtures. This phenomenon indicates the existence of an altitude limit above which no fuel-flow rate will permit ignition with the particular injection and ignition system.

A comparison of the fuel flow required for ignition with that required for engine operation is of some practical interest. At sea level and zero Mach number, the fuel flows for operation at 1600, 2500, and 4000 rpm are approximately 40, 60, and 90 pounds per hour, respectively. The data of figure 4(a) show that fuel flows required for ignition may greatly exceed these values.

A similar comparison for altitude conditions is shown in figure 5. Lines of constant fuel-air ratio are superimposed on the 1600 rpm curves from figure 4(b). Fuel-air ratios in actual engine performance should not exceed 0.03 unless very low combustion efficiencies are encountered. Experimentally obtained ignitions required fuel-air ratios as high as 0.09; this fuel-air ratio would be expected to create abnormally high temperatures in a full-scale engine, at least momentarily.

As evident in figure 4, the ease of ignition of these fuels parallels the order of their volatility. In figure 6, values of critical fuel flow at 1600 rpm taken from the faired curves of figure 4(a) are plotted against the 10-percent evaporated temperature of the fuel to show the decrease in flow rate required for ignition as volatility increases. This relation offers a possible basis of comparison of fuel-ignition characteristics with reference to fuel volatility.

By the nature of the experimental work, sharpness of definition of the critical fuel flow was limited. At some conditions, W_{f+} was actually less than W_{f-} (table II) indicating that ignition is uncertain in the range between these fuel flows. The greatest probability for error is found at points with very high fuel flow and at points where the ignition and nonignition zones overlap.

The necessary mixture of fuel vapor and air in the vicinity of the spark may be provided either by normal fuel evaporation at combustor-air temperature or by fuel-droplet vaporization on the hot electrodes. The droplets may reach the electrodes either by direct impingement of the spray cone or by recirculation within the primary air zone. Inasmuch as both the angle of the spray cone and the size of the droplet may be greatly affected by the fuel temperature (at a given fuel-flow rate), a photographic examination of the three fuels was conducted at various flows and temperatures.

Comparison of spray angles produced by the different fuels under similar conditions can be made by reference to figure 7. These photographs were taken with the spray discharging into quiescent air and therefore cannot precisely correspond to sprays in the combustor. Trends with temperature and fuel flow should, however, be similar.

As is shown by the photographs in figure 7(b), a decrease in fuel temperature resulted in a contraction of the spray cone with attendant increase in droplet size, these effects being most pronounced at the very low fuel flows. At high flows, the changes due to temperature cannot easily be assessed by photographic examination.

Inasmuch as the narrowing spray cone prevents impingement on the electrodes and the greater droplet size hinders recirculation, it is evident that either phenomenon may cause an increase in critical fuel flow with temperature decrease.

The data presented in figure 4 were obtained from a single combustor using extensively extrapolated control curves and therefore must not be applied directly to any full-scale engine. Trends and relations, however, should be similar.

SUMMARY OF RESULTS

From ignition studies of two AN-F-58a fuels and AN-F-32 fuel in a single can-type turbojet combustor using standard injection and ignition systems, the following results were obtained:

1. The order of ease of ignition appeared to bear a direct relation to volatility as indicated by the 10-percent evaporated temperature.

2. Fuel-flow rate required for ignition increased with increase in preignition engine speed.

3. Increase in altitude required, in general, an increase in fuel flow for ignition.

4. Decrease in ambient temperature at sea-level conditions required an increase in fuel flow for ignition.

5. Fuel flow required for ignition may greatly exceed that required for operation at high-altitude or low ambient-temperature conditions.

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2. Wear, Jerrold D., and Douglass, Howard W.: Carbon Deposition from AN-F-58 Fuels in a J33 Single Combustor. NACA RM E9D06, 1949.

3. Brombacher, W. G.: Altitude-Pressure Tables Based on the United States Standard Atmosphere. NACA Rep. 538, 1935.

4. Gooding, Richard M., and Hopkins, Ralph L.: The Determination of Aromatics in Petroleum Distillates. Papers Presented before Div. Petroleum Chem., Am. Chem. Soc. (Chicago, Ill.), Sept. 9-13, 1946, pp. 131-141.

TABLE I - SPECIFICATIONS AND ANALYSES OF FUELS

	Specifications		Analysis		
	AN-F-58a	AN-F-32	AN-F-58a		AN-F-32
			49-245	49-162	48-306
A.S.T.M. distillation D 86-46, °F					
Initial boiling point	-----------	-----------	99	109	340
Percentage evaporated					
5	-----------	-----------	113	135	350
10	-----------	410 (max.)	128	158	355
20	-----------	-----------	148	210	360
30	-----------	-----------	187	270	364
40	-----------	-----------	243	323	367
50	-----------	-----------	292	360	375
60	-----------	-----------	334	398	380
70	-----------	-----------	374	432	384
80	-----------	-----------	416	460	391
90	400 (min.)	490 (max.)	463	500	402
Final boiling point	600 (max.)	572 (max.)	548	584	440
Residue, (percent)	1.5 (max.)	1.5 (max.)	1.0	1.0	1.0
Loss, (percent)	1.5 (max.)	1.5 (max.)	1.5	1.0	1.0
Freezing point, °F	-76 (max.)	-76 (max.)	< -76	< -76	< -76
Accelerated gum, (mg/100 ml)	20 (max.)	8 (max.)	7	16	0
Air-jet residue, (mg/100 ml)	10 (max.)	5 (max.)	2	8	1
Sulfur, (percent by weight)	0.50 (max.)	0.20 (max.)	< 0.50	< 0.50	< 0.02
Aromatics, (percent by volume) A.S.T.M. D-875-46T	25 (max.)	20 (max.)	15	25	15
Silica gel[a]			[b]17	[b]31	15
Specific gravity	0.728 (min.) 0.802 (max.)	----------- 0.850 (max.)	0.757	0.801	0.830
Viscosity (centistokes at -40° F)	-----------	10.0 (max.)	2.4	4.1	9.2
Bromine number	30.0 (max.)	3.0 (max.)	12	12	0
Reid vapor pressure, (lb/sq in.)	5-7	-----------	7.0	4.5	(c)
Hydrogen-carbon ratio	-----------	-----------	[b]0.167	[b]0.150	0.154
Net heat of combustion (Btu/lb)	18,400 (min.)	-----------	[b]18,700	[b]18,500	18,530

[a]Determined by modified method of reference 4.
[b]Calculated values from base-stock data.
[c]Reid vapor pressure not measurable.

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TABLE II - TABULATION OF RESULTS

Flight Mach number	Engine speed (rpm)	Altitude (ft)	Ambient temperature (°F)	Critical fuel flows for ignition[a]								
				49-245			49-162			48-306		
				W_{f+} (a)	W_{f-} (b)	$W_{f,c}$ (c)	W_{f+}	W_{f-}	$W_{f,c}$	W_{f+}	W_{f-}	$W_{f,c}$
0	1600	Sea level	90	17.4	15.2	16.3	19.7	27.3	23.5	39.3	38.0	38.7
	2500			20.3	17.9	19.1	33.4	30.4	31.9	65.3	66.2	65.8
	4000			38.9	36.1	37.5	38.5	38.6	38.6	75.9	71.6	73.8
	1600		59	20.8	17.9	19.4	21.3	21.1	21.2	59.0	54.7	56.9
	2500			28.5	26.0	27.3	35.5	38.5	37.0	97.0	91.1	94.1
	4000			41.5	39.6	40.6	50.5	50.0	50.3	124.0	121.1	122.6
	1600		27	23.2	20.2	21.7	27.9	30.1	29.0	80.3	75.3	77.8
	2500			29.6	32.5	31.1	42.7	45.0	43.9	113.3	113.5	113.4
	4000			52.2	52.5	52.4	105.2	103.0	104.1		130.0	
	1600		-4	28.6	25.9	27.3	37.4	39.8	38.6	104.5	100.6	102.6
	2500			42.9	40.6	41.8	102.6	100.7	101.7		129.4	
	4000			73.6	69.4	71.5						
	1600		-36	36.6	39.3	38.0	52.4	56.6	54.5	140.6	132.7	136.7
	2500			64.9	61.3	63.1						
	4000			131.5	135.0	133.3						
	1600	5,000	40	20.8	19.3	20.1	27.6	24.2	25.9	61.3	49.0	55.2
	2500			23.2	20.6	21.9	32.9	30.2	31.6	83.5	75.6	79.6
	4000			46.9	44.6	45.8	52.6	53.3	53.0	127.1	124.7	125.9
	1600	10,000	24	22.8	24.6	23.7	29.9	27.0	28.5	74.2	69.4	71.8
	2500			25.9	23.5	24.7	32.7	29.7	31.2	103.4	103.0	103.2
	4000			44.6	41.9	43.3	49.9	48.4	49.2			
	1600	20,000	-12	23.4	23.6	23.5	51.6	50.3	51.0	90.9	87.8	89.4
	2500			36.5	34.0	35.3	37.9	35.8	36.9			
	4000			46.8	52.6	49.7	56.6	57.2	56.9			
	1600	30,000	-48				83.7	67.2	75.5			
	2500			52.1	52.7	52.4	77.4	77.2	77.3			
	4000			72.5	70.3	71.4						
0.6	1600	5,000	40	36.5	36.7	36.6	42.4	44.7	43.6	98.9	103.6	101.3
	2500			44.5	41.8	43.2	47.8	56.1	52.0	120.1	117.3	118.7
	4000			46.9	47.4	47.2	62.8	59.8	61.3			
	1600	10,000	24	25.1	33.1	29.1	42.7	40.8	41.8	97.9	97.5	97.7
	2500			44.8	42.0	43.4	61.0	65.9	63.5		117.3	
	4000			52.2	50.1	51.2	69.1	69.1	69.1			
	1600	20,000	-12	47.2	44.2	45.7	42.7	42.4	42.6	117.3	127.1	122.2
	2500			49.4	52.6	51.0	69.2	69.7	69.5			
	4000			65.4	80.0	72.7	106.9	107.3	107.1			
	1600	30,000	-48	57.0	52.0	54.5	57.1	57.2	57.2			
	2500			80.1	77.8	79.0	107.1	103.4	105.3			
	4000				134.1							

[a]Lowest flow in lb/hr at which ignition occurred.
[b]Highest flow in lb/hr that failed to ignite.
[c]Critical fuel flow; average of W_{f+} and W_{f-}.

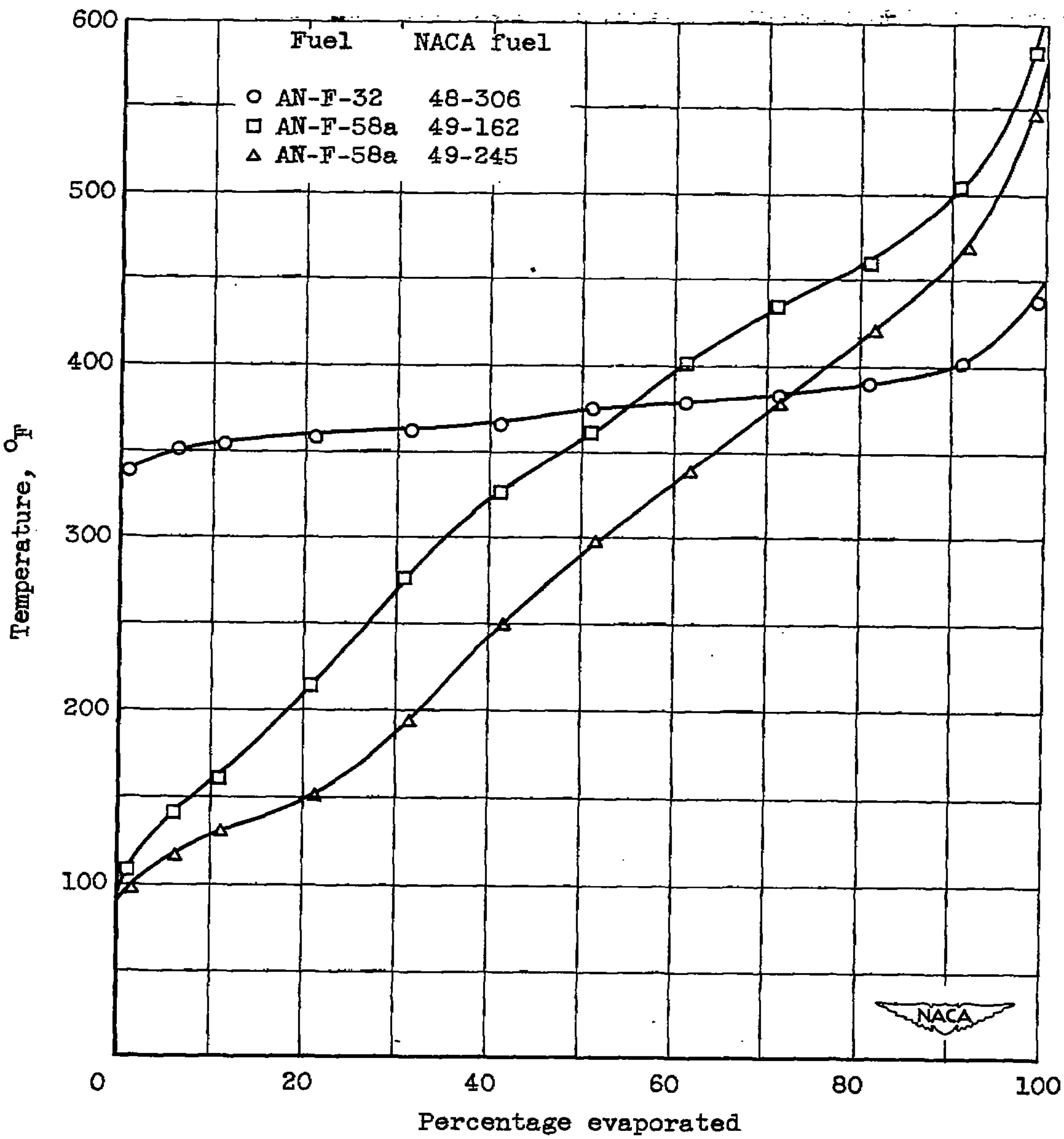

Figure 1. - Variation of distillation temperature with percentage evaporated for three fuels.

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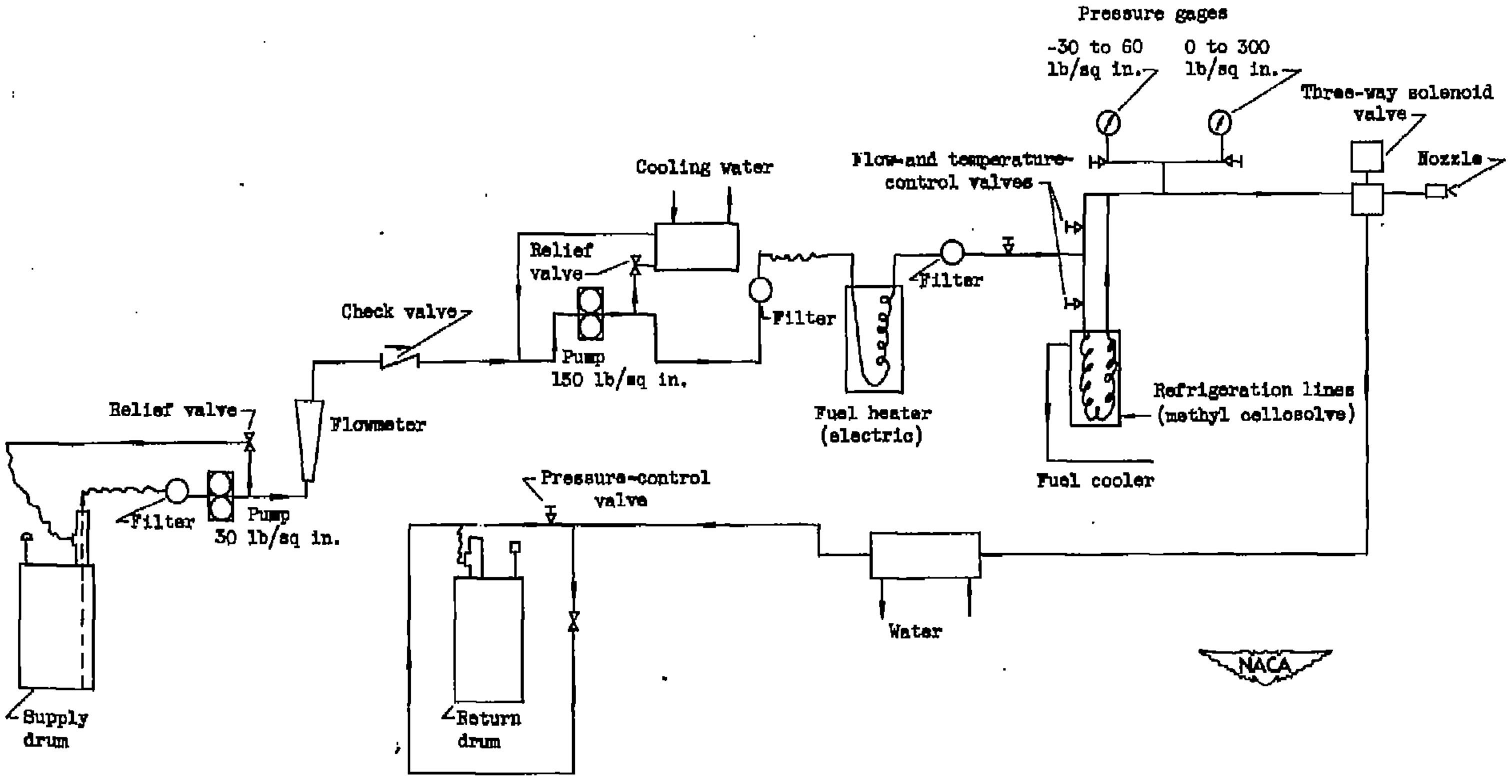
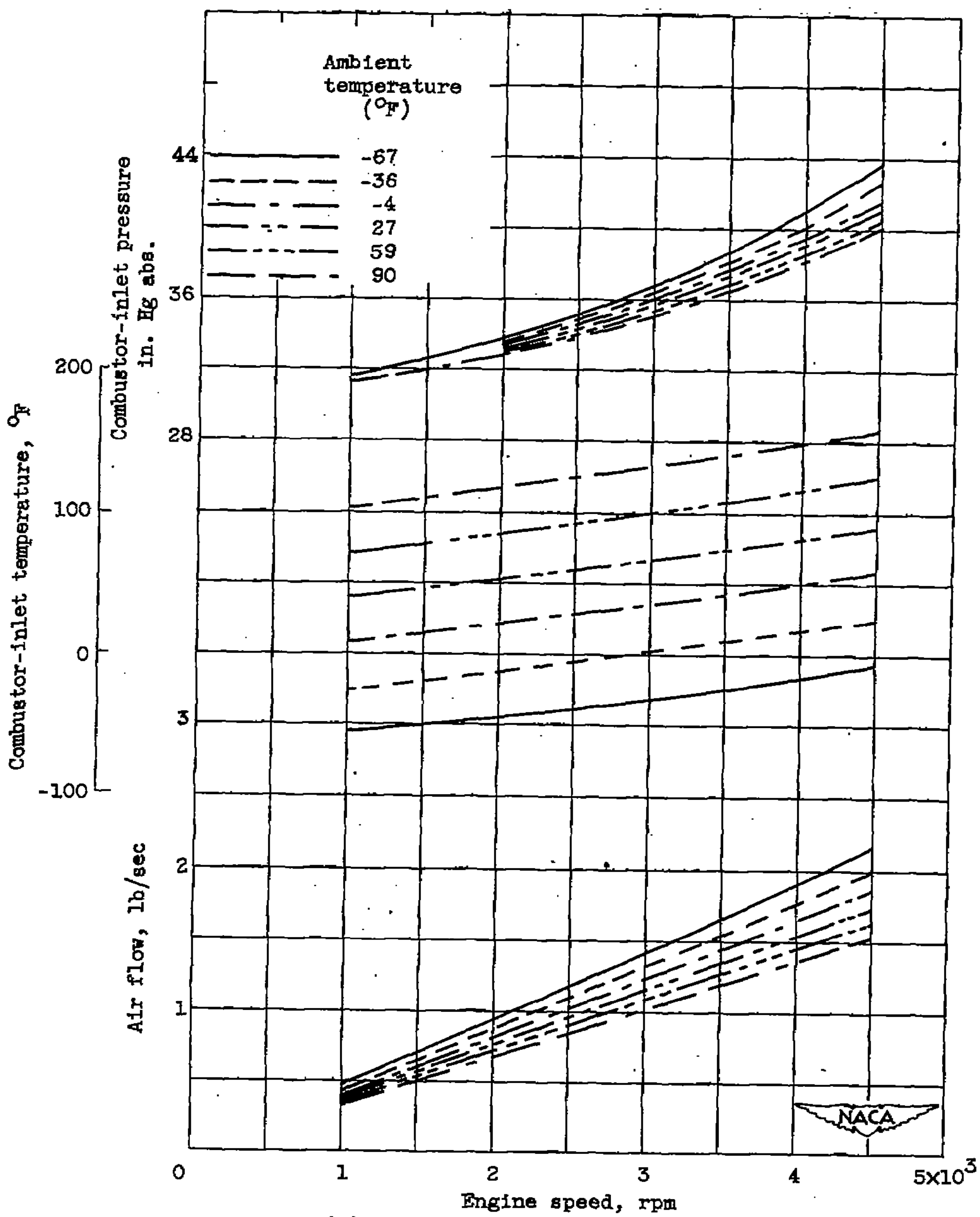


Figure 2. - Schematic diagram of fuel system used in ignition studies.



(a) Sea level; flight Mach number, 0.

Figure 3. - Variation of air-flow parameters for single can-type combustor.

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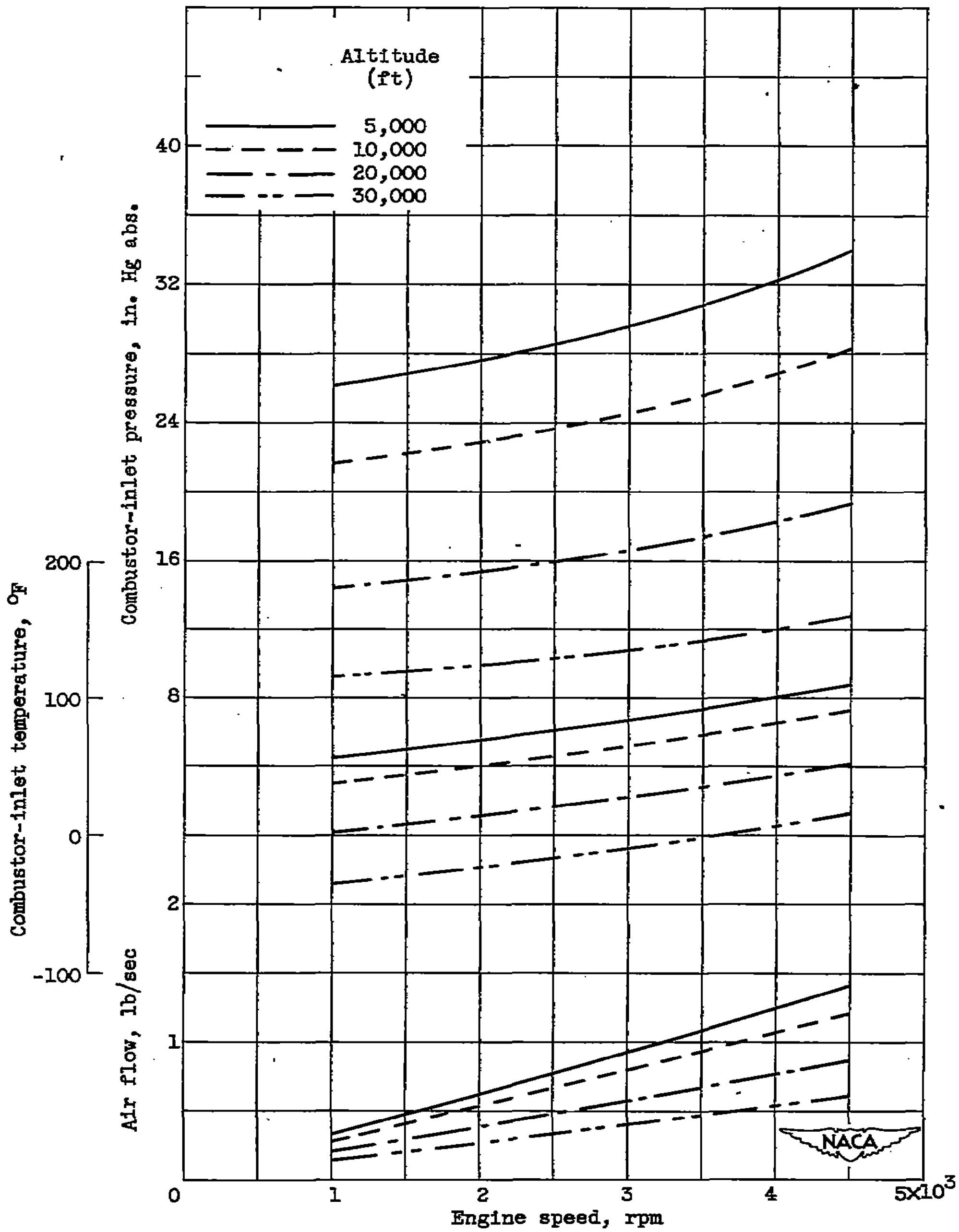
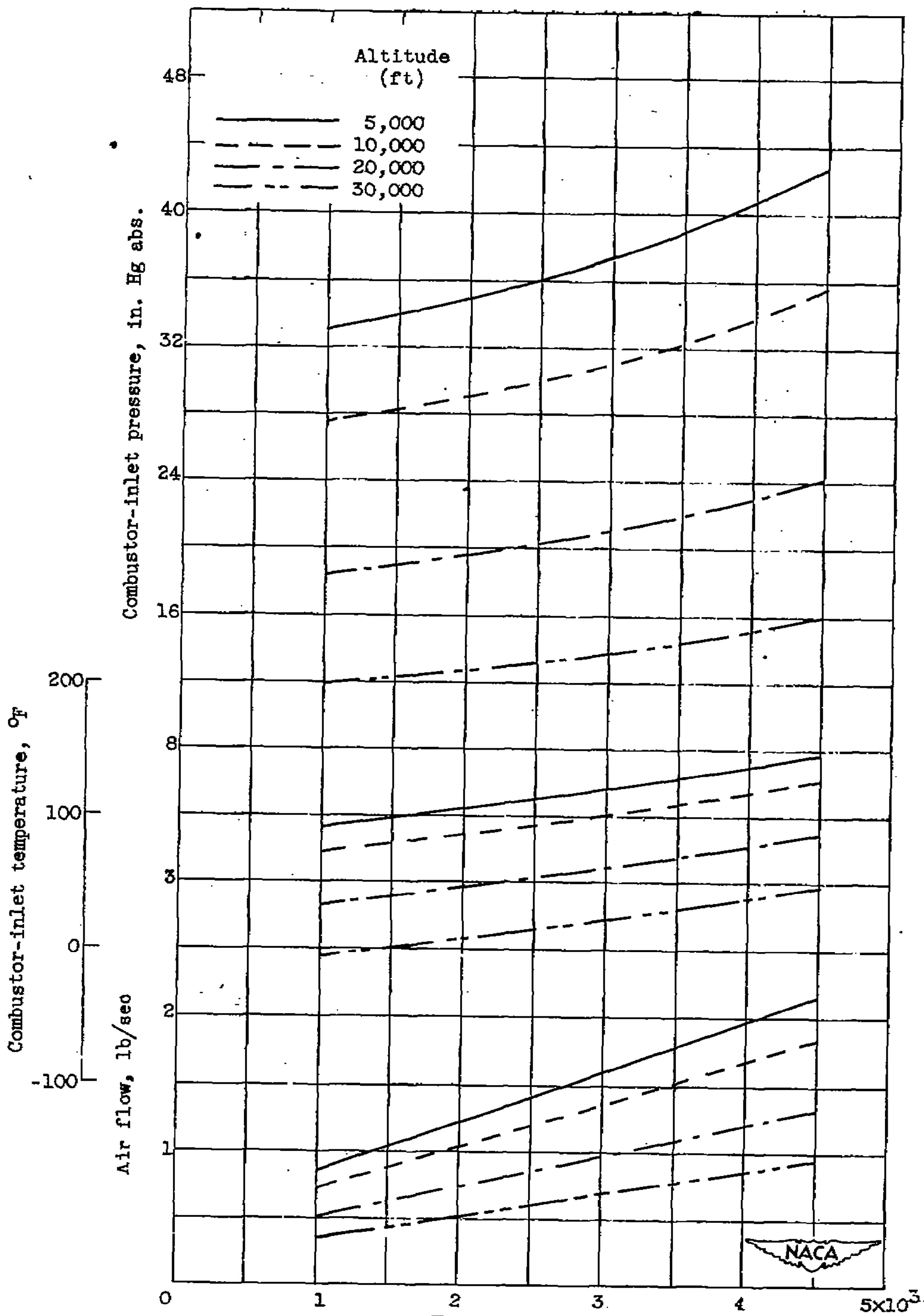


(b) Flight Mach number, 0.

Figure 3. - Continued. Variation of air-flow parameters for single can-type combustor.



(c) Flight Mach number, 0.6.

Figure 3. - Concluded. Variation of air-flow parameters for single can-type combustor.

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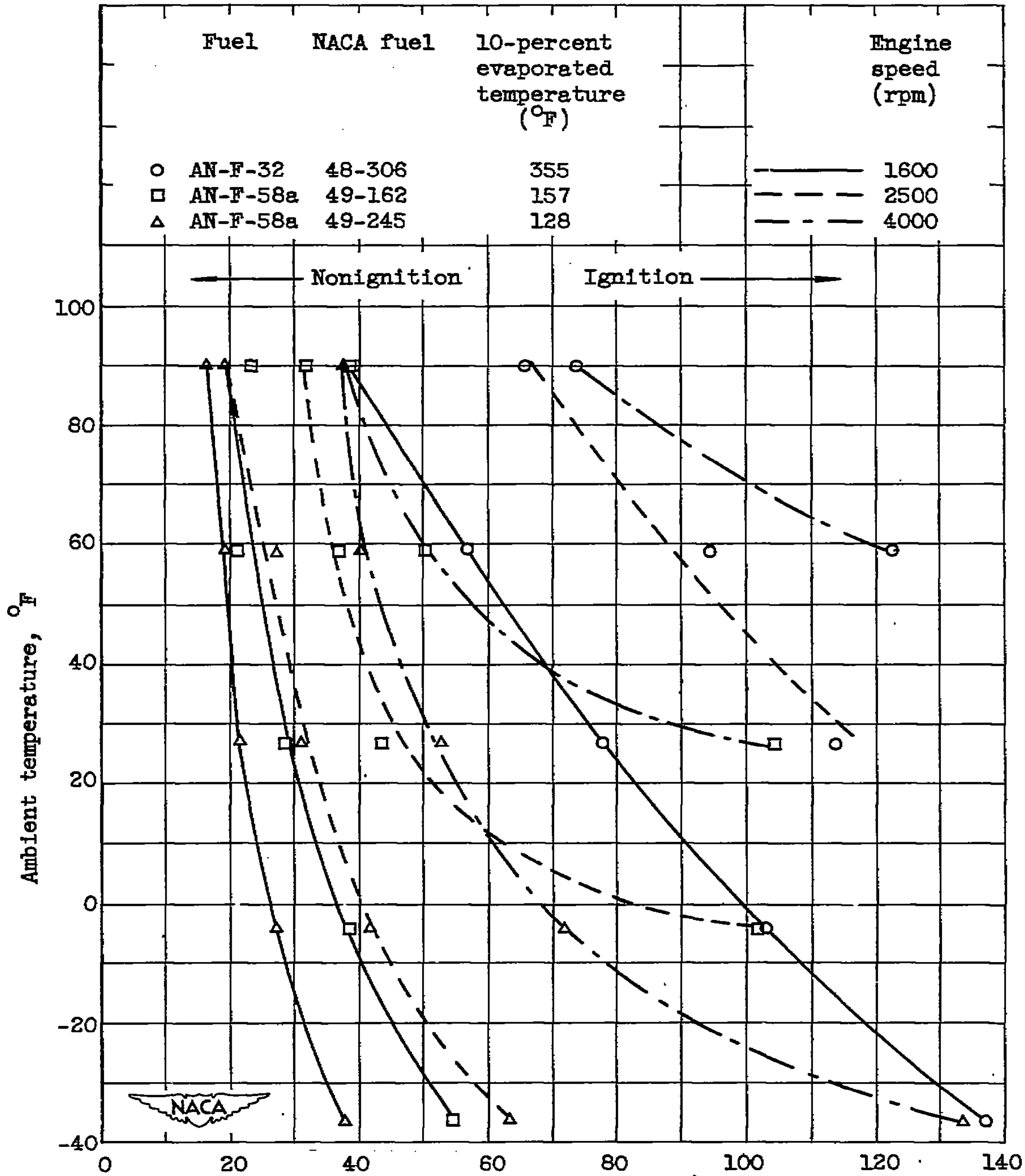

(a) Sea level; flight Mach number, 0.

Figure 4. - Effect of operating conditions on critical fuel flow for ignition for three fuels and three engine speeds.

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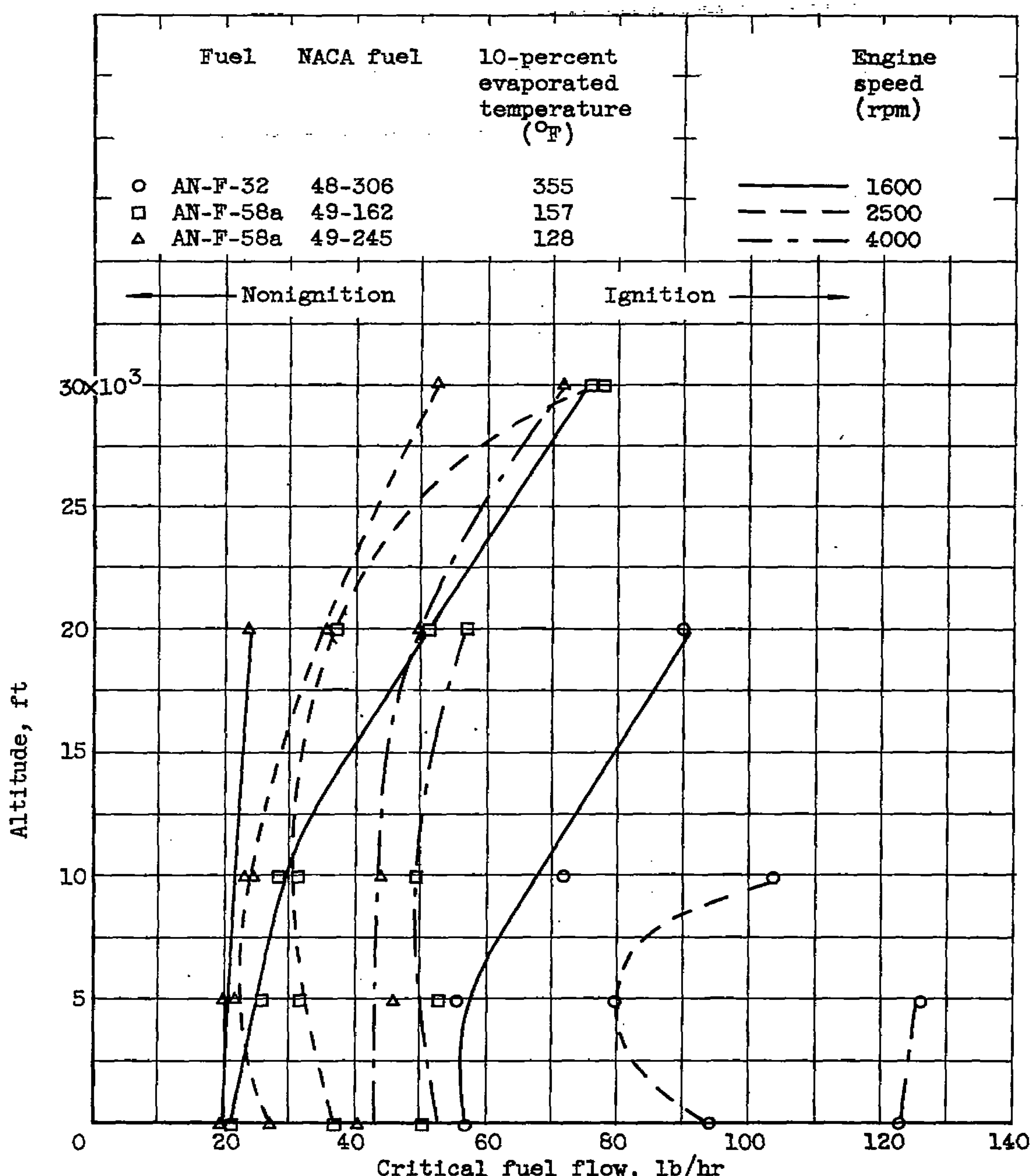
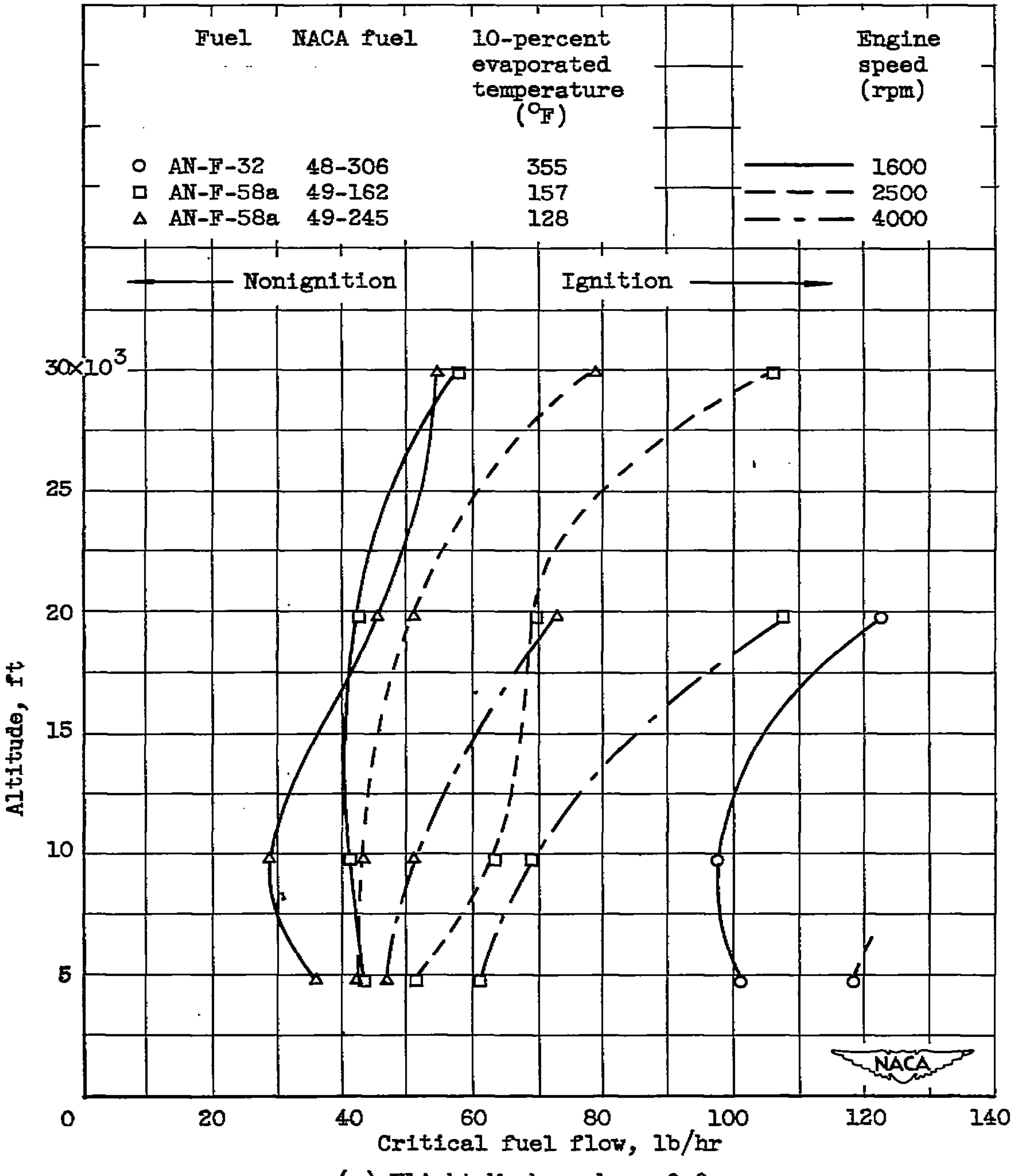


(b) Flight Mach number, 0.

Figure 4. - Continued. Effect of operating conditions on critical fuel flow for ignition for three fuels and three engine speeds.



(c) Flight Mach number, 0.6.

Figure 4. - Concluded. Effect of operating conditions on critical fuel flow for ignition for three fuels and three engine speeds.

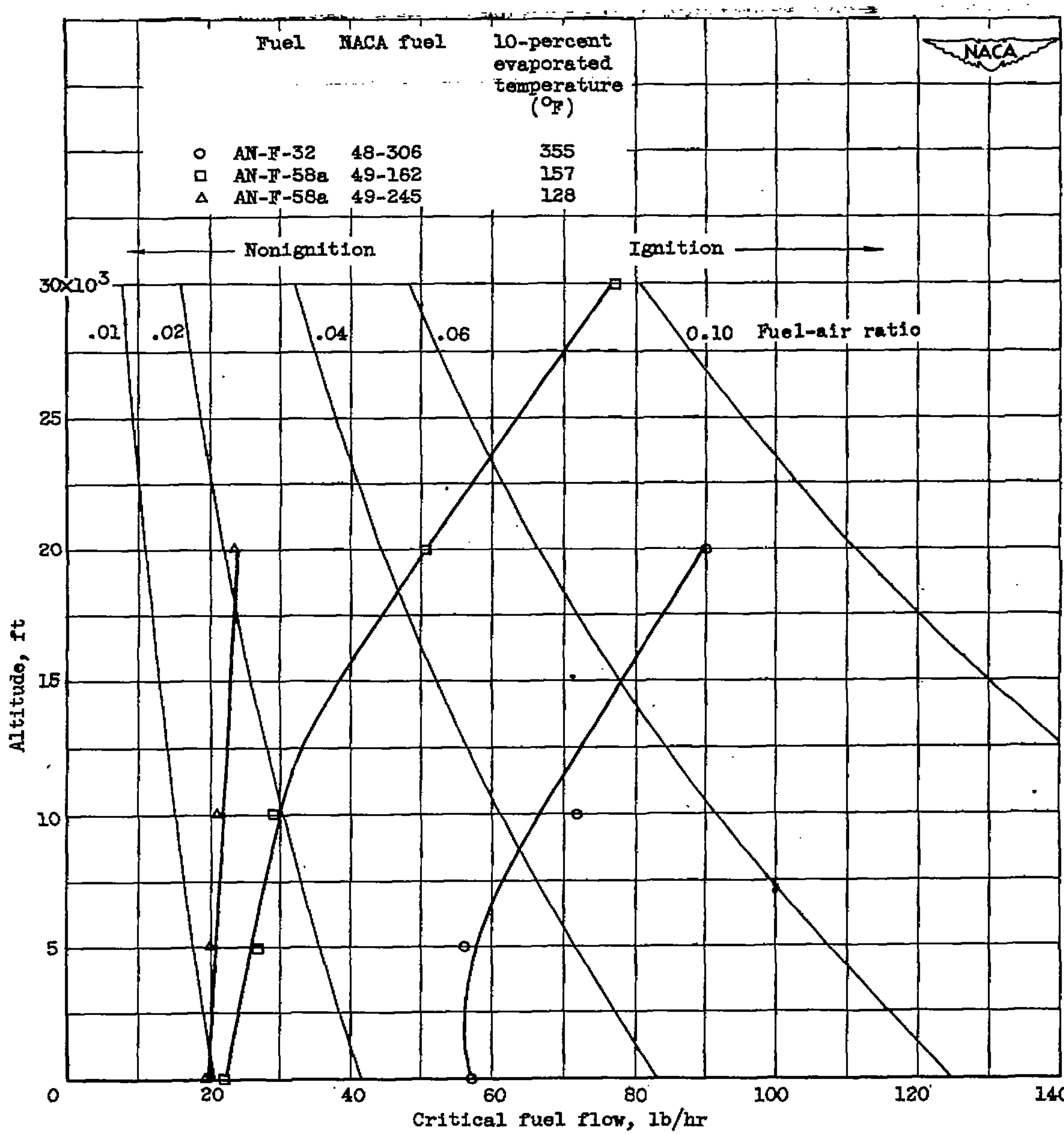


Figure 5. - Critical fuel flow for ignition for three fuels. Engine speed, 1600 rpm; flight Mach number, 0.

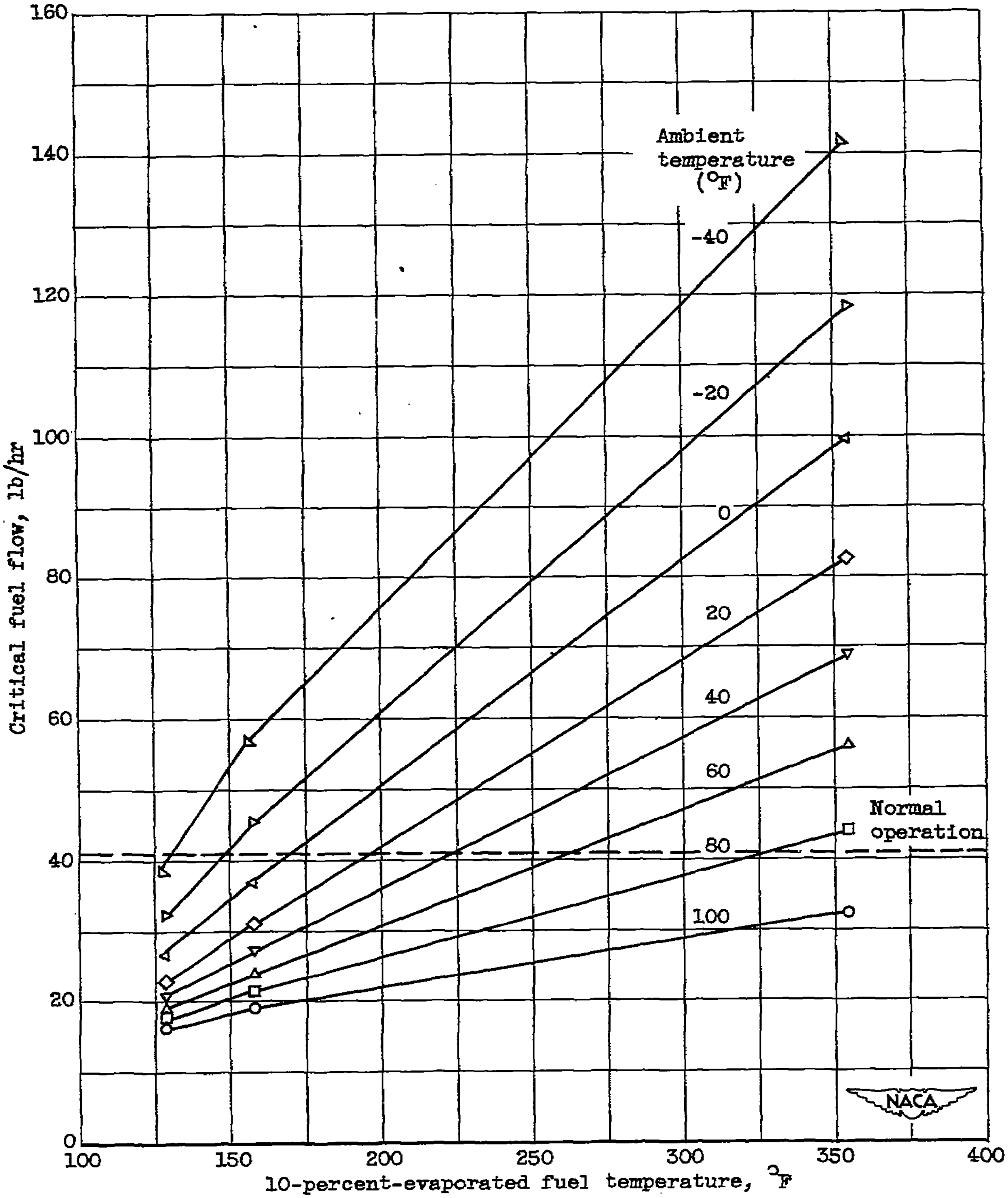
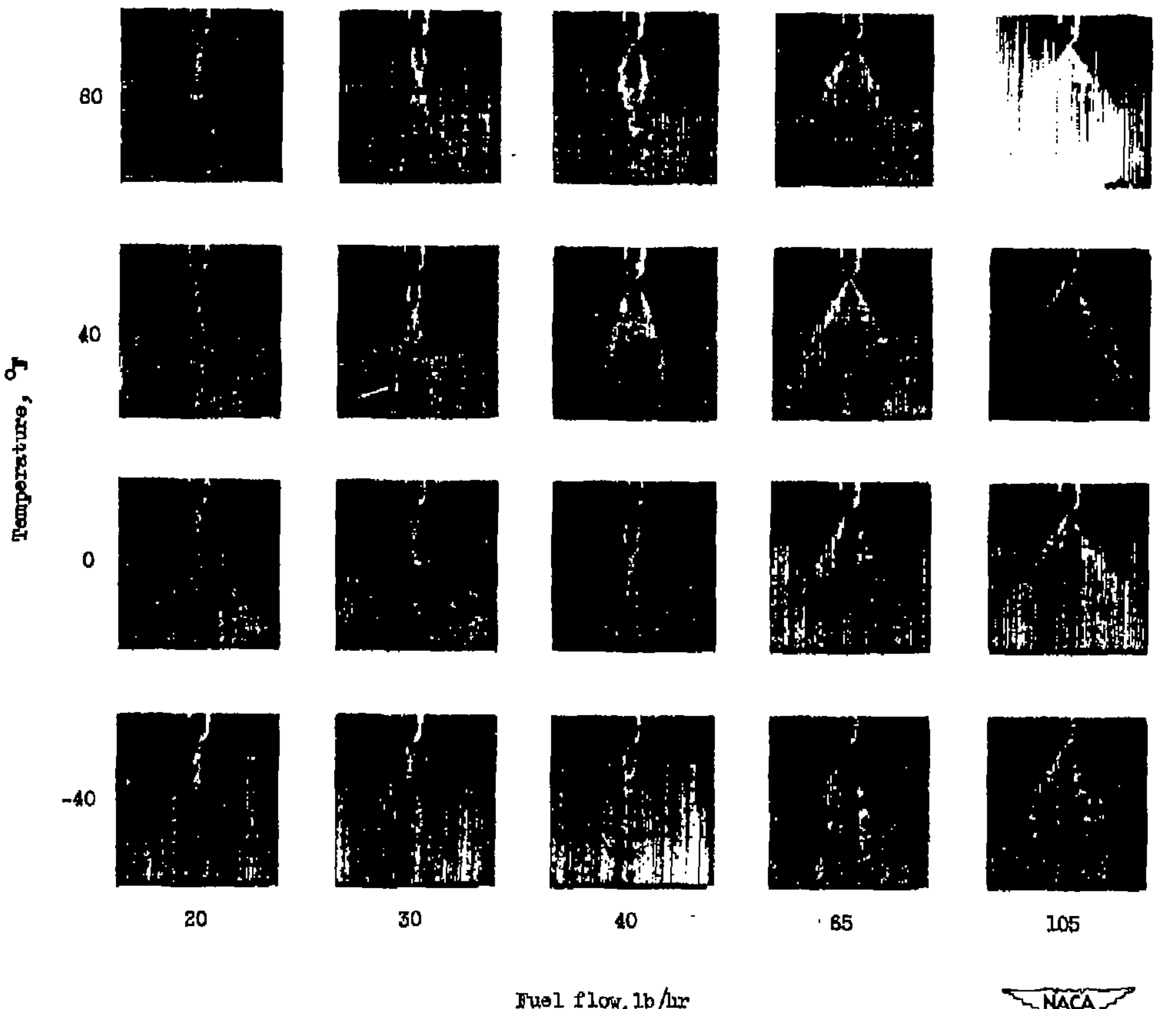


Figure 6. - Variation of critical fuel flow for ignition with fuel volatility at sea level. Engine speed, 1600 rpm; flight Mach number, 0.



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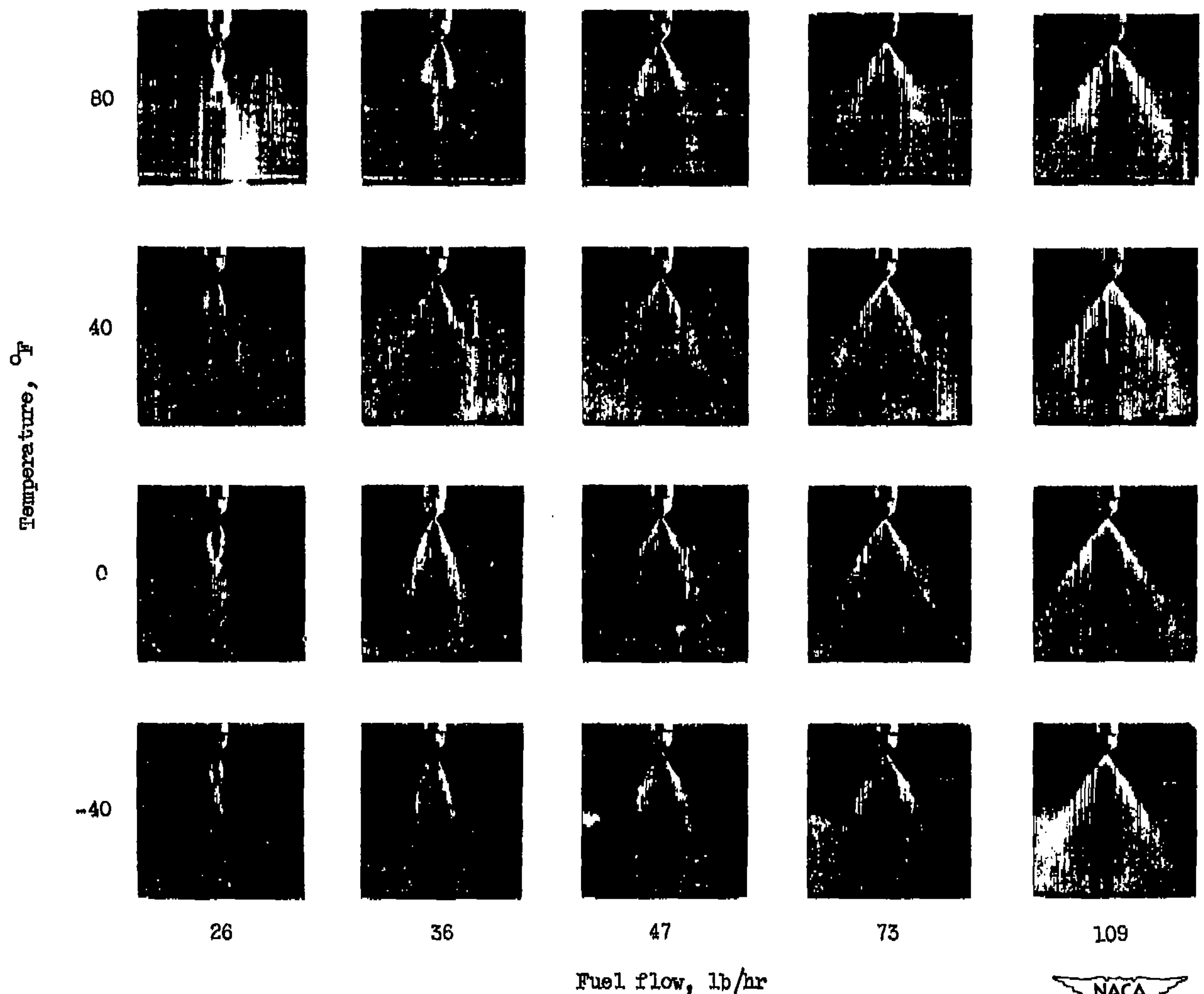
(a) Fuel, AN-F-32 (NACA fuel 48-306).

Figure 7. - Variation of fuel-spray characteristics with temperature and flow rate.



(b) Fuel, AN-F-58a (NACA fuel 49-245).

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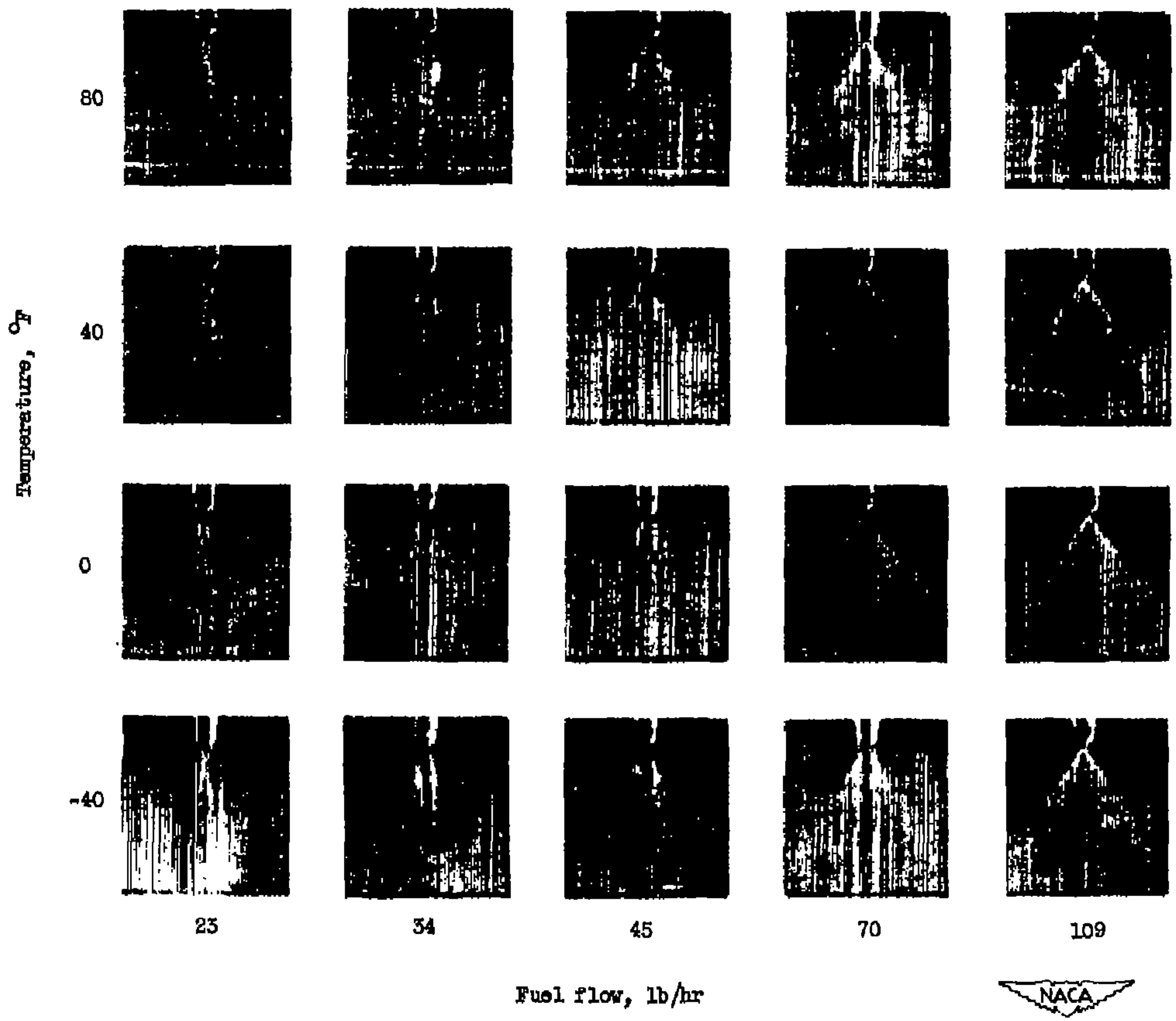
Figure 7. - Continued. Variation of fuel-spray characteristics with temperature and flow rate.



(c) Fuel, AN-F-58a (NACA fuel 49-162).

Figure 7. - Concluded. Variation of fuel-spray characteristics with temperature and flow rate.

NACA-Langley - 10-13-50 - 300